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SEARCH FOR FAST PARTICLES PRODUCED AT LARGE LAB ANGLES AT NAL

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A Proposal Submitted by

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ABSTRACT - An experiment is proposed to look for charged particles emitted at large lab angles that are normally forbidden kinematically. These particles if found would correspond to hitherto unobserved events such as the production of particles with imaginary mass values ("tachyons"). Also, we wish to look for fractionally-charged particles produced at these angles. These particles, if found, would correspond to strongly-bound quark-quark states formed in a dissociation of the target nucleon. The detection system will consist of wire-chambers, dE/dx and time-of-flight counters. The basic hardware is under construction and the final system will be ready for test runs at a lower-energy machine in six months. The detection telescope will view interactions of the primary proton beam from backward (in lab) directions and our first choice experimental site is the straight section B with a thin internal target. We would like to use the highest available beam at NAL and since our beam transport and intensity requirements are very minimal, we will be able to run parastically during the tuning periods of the NAL machine in the next year. The machine time required for this experiment is about three months.

SUMMARY OF THE PROPOSED EXPERIMENT

Purpose: Search for fast ($\beta > 0.5$) charged particles with a rigidity (= momentum/charge in units of e) greater than one GV emitted at large laboratory angles ($180^\circ > \theta_L > 90^\circ$.)

Theory: The law of the conservation of the four-momentum of an isolated system implies that in interactions involving a stationary target (mass = M_t), the maximum energy E_b which can be emitted at backward angles in the laboratory system ranges from $\frac{1}{2}M_t$ (at $\theta_L = 180^\circ$) to M_t (at $\theta_L = 90^\circ$). Therefore, any detection of particles with a rigidity greater than M_t (in units of GV) would imply hitherto unknown phenomena. We consider two possibilities:

(1) Tachyon (particles with an imaginary mass) production in which case, E_b may well exceed the "normal" limits *if* the tachyon "mass" is large engough; and

(2) Quark and/or quark-quark bound state production in which case, the rigidity may well exceed the "normal" limits if the mass involved is much less than M_t. [It is amusing to note that if quarks are produced in interactions that are of a long range and unsaturated, then it is plausible that M_t may be very large (whole nucleus or even several nuclei) in which case, even heavy quarks (say, $M_q \approx 6$ GeV) can be emitted at large angles in the laboratory system.]

Equipment: An array of six dE/dx counters will measure the charge of the relativistic particles. A set of wire-chambers and plastic counters will be used to reduce noise signals. A small magnet will be used to sweep out low rigidity (< one GV) particles. The system will be made flexible so that the range of lab angles 90° to 180°, can be covered in a small space (such as the Straight Section B). The basic components of the system already exist and we expect the whole system to be ready for testing in six months.

Target: Heavy Z material. We will be able to use an internal target in the Straight Section B.

Beam: No special requirements on the beam characteristics. However, we prefer lower intensity beams. Also, we prefer the highest possible energy beam at NAL.

Special Requirements on NAL: None

I. INTRODUCTION

A. Quark Production

If quarks really exist, it is probable that some high energy interactions involve "quasi-free" quark targets and an appreciable number of "spectator" quarks may be emitted with small relative momenta. If quark-quark interactions are strong, then these spectator quarks may frequently form bound states with a small mass. And if the mass of these bound states is low enough, then these quark-quark "particles" may be emitted at large angles in the laboratory system. The two spectator quarks may form qq bound systems of 4/3, 1/3 and -2/3 charges and only the 4/3 charge will be missed in the proposed experiment. Of course, the -2/3 combination would be present if a target other than H_2 is used.

If this picture of quark and quark-quark production is correct, then the effective production cross-section would be given by $\sigma_q = \eta\sigma_{qh}$ where σ_{qh} is the total quark-hadron interaction cross-section and η is the "incoherence" factor (i.e., a measure of the extent of the validity of the "impulse" approximation). This factor would be small near the threshold but should increase with the incident energy. Various estimates of σ_{qh} are given in Table I. Since σ_{qh} may be much larger than the "normal" quark production cross-section, it is probable that quarks are produced predominantly through the model described above at the NAL energy and therefore, detection of less-than-minimum ionizing particles produced at large angles would be a new and perhaps the best way of looking for quarks at NAL.

Numerous attempts were made during the last decade[1] to find the quarks, but only a few marginally positive evedences[2,3] have been reported so far. However, it is interesting to note that the quark "candidates" in these evidences seem to have the following features:

(1) The quarks were closely associated with large air showers,

(2) The quark (or a qq bound state) mass was less than about 6 GeV and the sea-level momentum observed was small[2],

(3) The quarks were not parallel to the shower axis and they were consistent with having been produced locally, e.g., in shielding, magnet, lower atmosphere, etc., and

(4) The observed quark frequency is consistent with an effective quark production (or interaction) cross-section of the order of one mb.

It should be noted that these features of quark production, if true, would explain some of the negative results reported by various cosmic-ray groups.[1,4]

Quark searches done at proton machines[5-7] have been so far sensitive only to relatively high momentum and forward (0^o to 20^o) quarks produced presumably in reactions such as $NN \to NNq\bar{q}$ and $\pi N \to Nq\bar{q}$ [8]. The latest proton machine experiment[5] places an upper limit of about 10^{-40} cm^2 on the quark production cross-section if $M_q \simeq 4$-5 GeV and if quarks were produced in forward directions with a large momentum.[9] Fig. 1 gives a summary of the maximum "sensitivity" achieved in various machine experiments. The solid curves in the figure represent the "best" estimates on the quark-antiquark pair production cross-section as quoted in Ref. 1. It should be noted that if $q\bar{q}$ pairs are indeed produced in the same manner as $N\bar{N}$, $Y\bar{Y}$, etc, are produced at lower energy machines, then the sensitivity reached in the proton machine experiments[1] was either marginal or well above the predicted cross-section. Indeed, if one takes $M_q = 6$ GeV, one would have $\sigma_{q\bar{q}} \simeq 10^{-50}$ cm^2.

B. Tachyon Production

In the general reaction $P_a + M_t = P_b + P_x$, where the subscripts a, t, b and x denote the incident, target, detected final state and "missing" final state particles, respectively, the missing mass squared is given by $M_x^2 \approx 2M_tE_a - 2E_aE_b + 2E_aE_b\cos\theta$ where θ is the lab production angle of particle b and $E_a \sim 200$-500 GeV and $E_b \approx |P_b|$. It is readily seen that for $\theta \approx 180°$ the missing mass becomes imaginary unless $M_t > 2E_b$ (or $M_t > E_b$ for $\theta \approx 90°$) and any presence of backward particles with energy greater than a few GeV in lab would imply hitherto unkrown reactions (assuming a hydrogen target).

High energy particles may be emitted at "forbidden" angles if particles with imaginary mass (tachyons)[10] are produced. Attempts to find tachyons have until now been of limited extent. Tachyon searches have been made in low energy photoreactions[11] and also in bubble chamber pictures[12] with negative results.

Tachyons may be produced in reactions such as $N + N \rightarrow N + N + T$ and due to the negative mass square of tachyons (T), high energy nucleons may be emitted at large lab angles. For example, in the extreme case that one of the nucleons remains stationary in lab, the other nucleons may be scattered backward ($\theta = 180°$) if the tachyon is produced in the forward direction. Then the energy of the scattered nucleon would be $E_b = (4M^2 + m^2)/4E_a$ where M is the nucleon mass and m^2 is the negative square of the tachyon "mass" (for $E_a = 200$ GeV and $E_b = 1$ GeV, $m \sim 28$ GeV).

Experimental observations of large angle and high energy particles in lab would constitute strong evidence for (but not proof of) the existence of tachyons, but more detailed examinations of the interactions in which backward particles are emitted will be required for any conclusive search for tachyons.

In the proposed experiment, we will search for high energy backward (normal dE/dx) particles and more definitive experiments will be proposed in the secondary beam area if we find any positive evidence for tachyons in this experiment.

C. Other Possibilities

It is very unikely but neverthless it is probable that the incident particle interacts with a group of nucleons as a whole in a high-Z target. In such a case, large angle and high energy particles can be enitted in the laboratory system.

Fig. 2 gives an estimate of the solid angle for particles that are produced isotropically in the production CM system with a velocity larger than that of the CM system. As is well-known, the solid angle involved is very small for target masses less than 20 GeV. However, these particles may be backward-peaked in the CM system in which case, the effective solid angle would be much larger than that implied in the figure.

High enegy interactions in high-Z materials produce a large flux of low energy (about 20 MeV average kinetic energy) nucleons nearly isotropically in the laboratory system[13]. Our detection system will be shielded against these "boil-off" nucleons.

High-energy large angle particles from interactions with heavy nuclei (i.e., "coherent" interactions) would be interesting in their own rights, but it would be difficult to distinguish these interactions from the effects of interactions with quasi-free nucleons with a large Fermi momentum. These particles will of course fake the tachyon production in our present set-up, but the use of a hydrogen target should eliminate this particular background. If the flux of these particles turn out to be very large at the NAL energy, we will have to use a light-Z target in a secondary beam area in order to achieve a reasonable limit of sensitivity for our quark search.

A small sweeping magnet will be used to sweep out low rigidity (less than one GV) particles coming from the target.

II. Experimental Methods

The main objective of the proposed experiment is to detect relatively fast (beta of 0.5 to 1.0) fractionally charged particles. We plan to detect these particles through their less-than-minimum dE/dx in liquid scintillators. A secondary objective of the experiment is to look for normal dE/dx particles emitted at large lab angles with high momentum (two or more GeV/c). This part of the experiment will constitute a preliminary phase of a later experiment to look for tachyons at NAL.

The basic logic of the detection system is shown in Fig. 3. It should be noted that both the normal and quark events will be detected concurrently in the system.

A. Detection System

The system is designed to measure: (1) the energy deposited by charged particles in liquid scintillators, (2) the particle velocity, and (3) the number and the direction of particles triggering the system. The solid angle acceptance of the system is defined by a set of plastic scintillators, P_1 to P_5. The plastic scintillators are also used for the time-of-flight of the particles. The paired counters P_1 and P_2 and the pair P_3 and P_4 are separated by about 5 meters.

The array of six liquid scintillation counters (about 5x50x50 cm^3 each) is used for the dE/dx measurement. Each counter is viewed by four phototubes and pulses from these tubes are mixed per counter and ADC'd into the PDP-8 computer.

The magneto-strictive wire-chambers S_1 to S_6 are used to count the number of particles passing through each liquid scintillator. They are also used to ensure that the detected particle originates in the target.

The PDP-8 computer (Indiana State University) has 8,192 words of memory, two magnetic tape drives and a storage CRT unit. The computer is expected to read in the ADC-bits (time-of-flight, dE/dx, and wire-chamber data) in less than one msec per event. This is comparable to the wire-chamber dead-time. During the interval between beam pulses, some routine tests on the performance of the system will be made. All pertinent data will be recorded on magnetic tapes for off-line data analysis.

The wire-chambers and their interface to the computer are being constructed at Indiana State University and the basic detection-logic system is being designed at ISU and the Ohio State University with the help of Mr. C. Rush (an electronics engineer). We expect to have the basic system ready in six months for testing and debugging, initially with cosmic rays but later on with an accelerator beam at a lower-energy machine.

The basic components of the PDP-8 software for our system already exist and we plan to do an exhaustive simulation study of various backgrounds in the on-line as well as the off-line computers in order to optimize our detection system. Therefore, the detection system described in this proposal will most likely be different from the "final" version of the system.

In view of the absence of any reliable estimate on radiation backgrounds in the proposed experimental site, the plastic counters, P_1 to P_5, will be used as an independent system to survey the radiation backgounds in the very first phase of this experiment. This survey should allow us to optimize the shielding and it should also ascertain the feasibility of using the Straight Section B for this experiment.

B. Resolution and Backgrounds

The detection system described in Section IIA should "minimize" problems arising from dE/dx straggling[14], small pulses due to locally emitted electrons (Compton electrons, pairs, etc), particles produced upstream of the target, etc. The inclusion of wire chambers is to remove ambiguities due to sidewise showers or strange multi-particle events. The chamber also allows one (in principle) to correct the pulse heights for obliqueness of the particle and also for any non-uniformity of the dE/dx counters.

The dE/dx counters will be calibrated and standardized using accelerator beams and built-in light flashes. A preliminary calculation of the fluctuations in dE/dx (less than 20% for our range of β's for 5 cm - thick scintillators)[14] shows that a better than 70% efficiency for 2/3 charged particles (nearly 100% for 1/3 charge) with less than one in 10^{12} of the background particles contaminating the quark sample.

As mentioned earlier, pulses from each dE/dx counter will be digitized and stored on a tape for a complete statistical (χ^2) test to see if an event is compatible with being due to one unique particle going through all the dE/dx counters with the same mean energy loss $\langle dE/dx \rangle$ in each counter.[15]

The cosmic-ray muon intensity in horizontal directions (zenith ~ $80° - 90°$)[16] is at most 10^{-3} μ/cm^2/sr/sec for $E_\mu > 1 - 2$ GeV. This will give rise to a background counting rate of about $2.5 \times 10^{-7}\mu$/msec ($\Delta\Omega = 2.5 \times 10^{-3}$ steradians, $\Delta A \simeq 100$ cm^2, effective area of the target covered by the telescope and one beam pulse ~ one msec long) or about 2.5×10^{-19} muons/pulse will simulate quarks in our system. Assuming 10^{10} protons/pulse and a target thickness $\rho t \simeq 100$ gm/cm^2, this background corresponds to a quark production cross-section of about 10^{-50}cm^2.

C. Expected Event "Rate"

If our quark production model is correct and if the "incoherence" factor is not too small at the NAL energies and if the quark-nucleon interaction cross-section is not much smaller than the values given in Table 1, then one would expect a fairly hot flux of quarks at NAL.

The expected quark flux per pulse is given by:

$$N_q = \sigma_{qh} N_o N_p \rho t \Delta\Omega \eta \epsilon \quad \text{, where}$$

N_q : quark flux per pulse.

σ_{qh} : quark-hadron interaction cross section: we take it to be 10^{-30} cm^2.

N_p : proton flux per pulse, about 10^{10} ppp.

N_o : Avogadro's number, 6×10^{23} nuclei/gram mole.

ρt : target thickness, 100 grams/cm^2, effective.

$\Delta\Omega$: 2.5×10^{-3} steradian.

η : "incoherence" factor, 10^{-2} (a wild guess).

ϵ : Lorentz factor for the solid angle, 10^{-2} (a wild guess).

Therefore, we would expect about one quark in every ten pulses. If one assumes one pulse per minute, we would have about 50,000 quarks per year. In case of negative results, we would like to run for about three months (parasitically, of course). This will give us a sensitivity of about 10^{-35} cm^2 for quark detection. As shown in Fig. 1, this sensistivity is comparable to that achieved in the quark search experiments done at lower energy machines.

III. NAL Requirements

A. Beam

Beam energy: as high as possible - ideally, 500 GeV or higher.

Beam intensity: 10^{10}ppp and one pulse/min. or faster.*

Beam shape: any shape (emittance); flat-topping preferred.

Beam purity: not required.

*This is for an internal target in the straight section B.

B. Shielding

Our equipment will come with some thin (one or two cm-thick Cu) shielding. This shielding will be adequate only for low energy charged particles and photons and we expect the NAL to provide the main shielding for neutrons and high energy particles. For the use of an internal target (our first choice), we will provide some additional shielding blocks for low energy neutrons. These shielding blocks will be in small modular units for maximum mobility inside the tunnel.

C. Experiment Site

First Choice - Straight Section B: A possible layout for our equipment in this area is shown in Fig. 4. A low intensity beam and a thin target are to be used. The equipment (including shielding) will be made very compact and mobile so as not to block the traffic in the area.

Second Choice - Highest energy external beam. The layout would be the same as in Fig.4. Since our beam requirements are very minimal, we will be able to use essentially any high energy beam, used or otherwise. We should be able to use tired and old beams just prior to a beam dump with a moderate amount of shielding.

D. Shelters

We will need some form of shelters for the electronics equipment. The equipment will need air-conditioning (particularly, the PDP-8). We expect to monitor our control equipment continuously and a working space for two or three experimenters should also be included in the shelter. If necessary, we will provide our own shelter (a trailer). We would, of course, like to place the equipment as close to the counters as possible.

E. Magnetized Iron Pieces

We expect a large flux of low rigidity (less than one GV) particles, mostly electrons and pions, in the backward directions and we will place 2-3 Kgauss-meters of magnetized iron pieces in our system. The field will be kept very low and also far away from the main beam (in case of the internal target). We expect the NAL to furnish these iron pieces with the associate power supplies, etc.

IV. Personnel

A. Ph. D. Physicists

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Y.S. Kim

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B. Graduate Students

E. Herring

S. Kirschner

J. Stevens

C. Electronics Engineers

J.W. Barbee

C.J. Rush

T. Massam, CERN 68-24 (1968, unpublished); L. Jones, Status of the Experimental Search for Physical Quarks (1969, unpublished).

[2] W.T. Chu, Y.S. Kim, W.J. Beam and N.W. Kwak, Phys. Rev. Letters **24**, 917 (1970)

[3] McCusker et al, Phys. Rev. Letters **23**, 658(1969); Phys. Rev. **186**, 1394 (1969).

[4] R.K. Adair and H. Kasha, Phys. Rev. Letters, **23**, 1355(1969).

[5] Yu M. Antipov et al, Physics Letters, **30B**, 576(1969).

[6] L.B. Leipuner et al, Phys. Rev. Letter, **12**, 423(1964).

[7] D.E. Dorfan et al, Phys. Rev. Letters, **14**, 999(1965).

[8] J. Orear, "Some Reactions at High Momentum Transfer at NAL", CLNS-101 (1970, unpublished).

[9] The Serpukhov experiments (Ref.5) looked for particles with a rigidity exceeding the maximum rigidity possible for singly charged particles. If our quark production picture is correct and if the interacting quarks are backward-peaked (in CM), then these quarks would have a low laboratory momentum and they would be missed in an "over-maximum" rigidity experiments.

[10] O.M.P. Bilaniuk, V.K. Deshpande and E.C.G. Sudarshan, Am.J. Phys. **30**, 718(1962); G. Feinberg, Phys. Rev. **159**, 1087(1967); E.C.G. Sudarshan, in "Elementary Particle Theory" (edited by N. Svarthalm, Almquist and Wiksell, Stockholm 1969), p 335.

[11] T. Alväger and M. Kreisler, Phys. Rev. **171**, 1357(1968).

[12] C. Baltay, G. Feinberg, N. Yeh and R. Linsker, Phys. Rev. D1,759(1970).

[13] B. Rossi, High Energy Particles, (Prentice Hall, Inc., New York, 1952) p449.

[14] Yu. K. Akimov, Scintillation Counters in High Energy Physics, (Academic Press, New York, 1965) pp5

[15] H. Kasha, L.B. Leipuner, and R.K. Adair, Phys. Rev. 150, 1140(1966).

[16] M.G.K. Menon and P.V. Ramana Murthy, in Progress in Elementary Particles and Cosmic Ray Physics, Vol. 9, p217 (John Wiley and Sons, Inc., New York, 1967.

Table I. Estimates on σ_{qh}*

σ_{qh} (cm^2)	Source
π ($\hbar/M_q)^2 \sim 10^{-29}$	Adair and Price[a]
σ_N $(M_\pi'/M_q)^2 \sim 10^{-29}$**	Dardo et al[b]
σ_N $(M_\pi/M_q) \sim 10^{-27}$	composition of jet particles
$1/3$ $\sigma_N \sim 10^{-27}$	Dooher[c]
$\sim 10^{-27}$	McCusker et al[d]
$\sim 10^{-27} - 10^{-26}$	Chu et al[e]

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* We assume $M_q \approx 6$ GeV.

** $\sigma_N \sim$ 40 mb, nucleon interaction cross-section

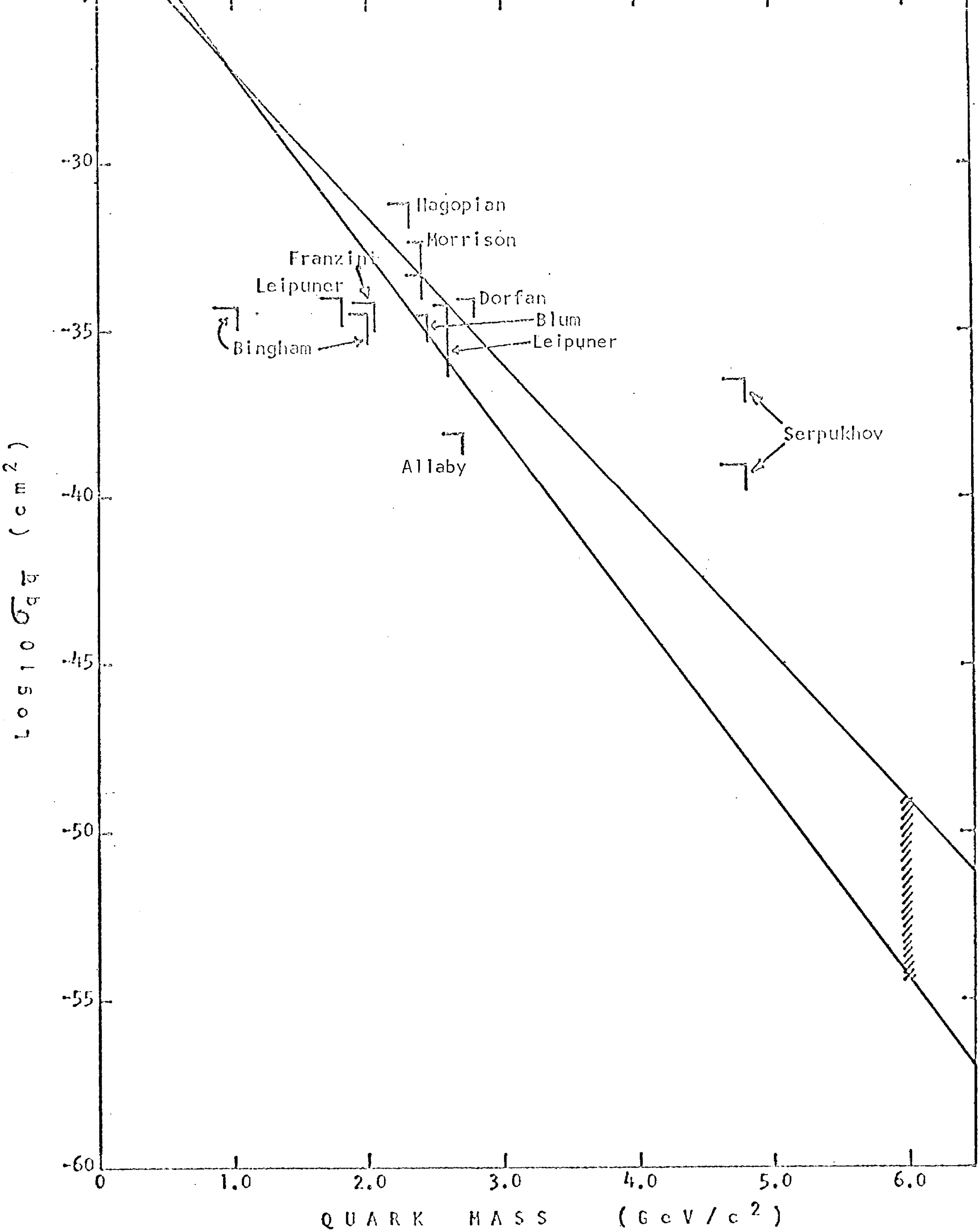
a R. Adair and N.J. Price, Phys. Rev. 142, 844 (1966)

b M. Dardo, P. Penengo and K. Sitte, Nuovo Cimento 58A, 59 (1968)

c J. Dooher, Phys. Rev. Letters 23, 1471 (1969)

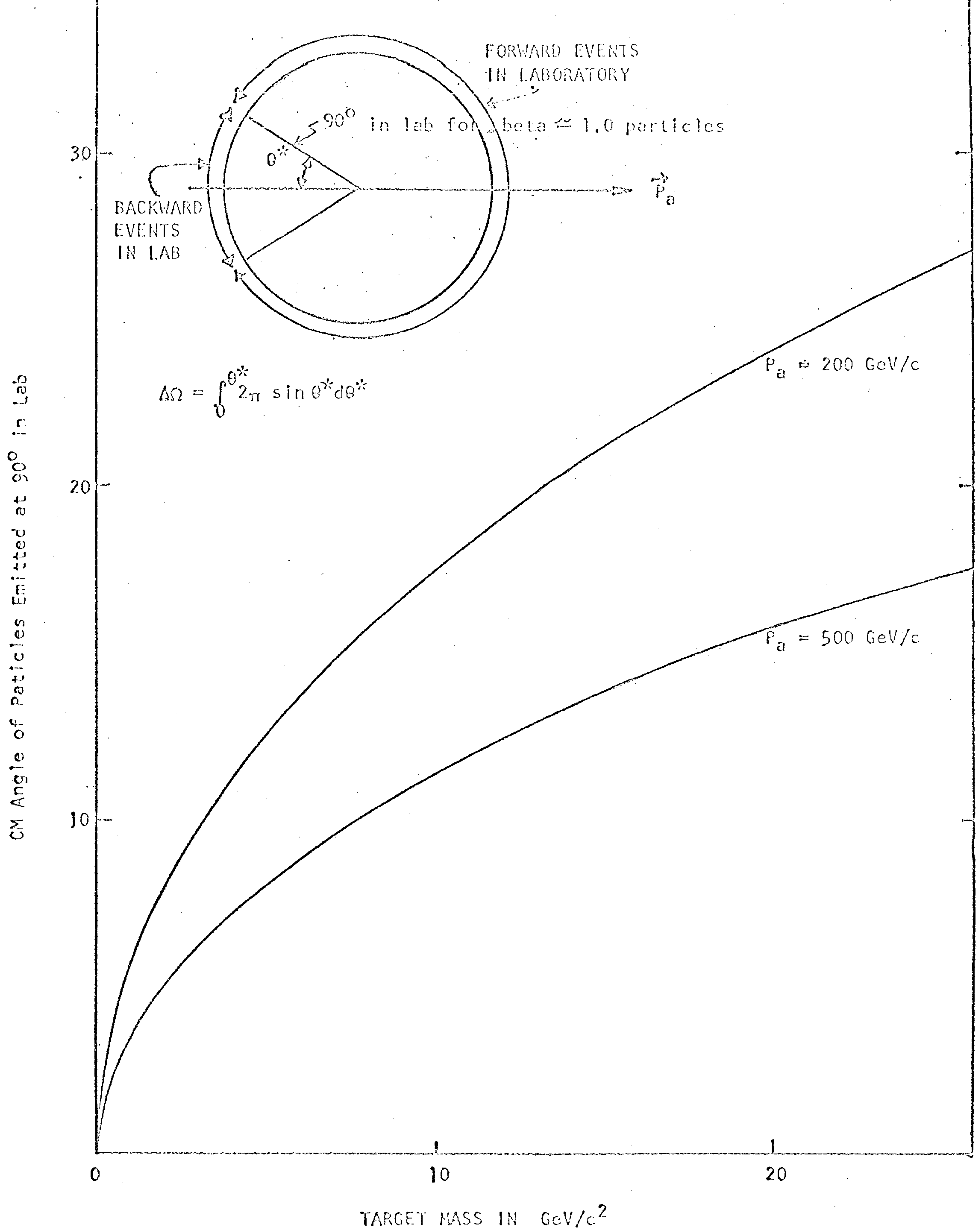
d McCusker et al, Phys. Rev. Letters 23, 658 (1969); also Phys. Rev. 186, 1394 (1969).

e W.T. Chu, Y.S. Kim, W.J. Beam, N.W. Kwak, Phys. Rev. Letters 24, 917 (1970)



Hagopian
Morrison
Franzini
Leipuner
Dorfan
Blum
Leipuner
Bingham
Serpukhov
Allaby
-30
-35
-40
-45
-50
-55
-60
0
1.0
2.0
3.0
4.0
5.0
6.0
QUARK MASS (GeV/c2)
Log10 σqq̄ (cm2)

Figure 1



FORWARD EVENTS
IN LABORATORY
90° in lab for beta ≃ 1.0 particles
θ*
BACKWARD
EVENTS
IN LAB
$\vec{P}_a$
$\Delta\Omega = \int_0^{\theta^*} 2\pi \sin\theta^* d\theta^*$
P_a = 200 GeV/c
P_a = 500 GeV/c
30
20
10
0
10
20
CM Angle of Paticles Emitted at 90° in Lab
TARGET MASS IN GeV/c²

Figure 2

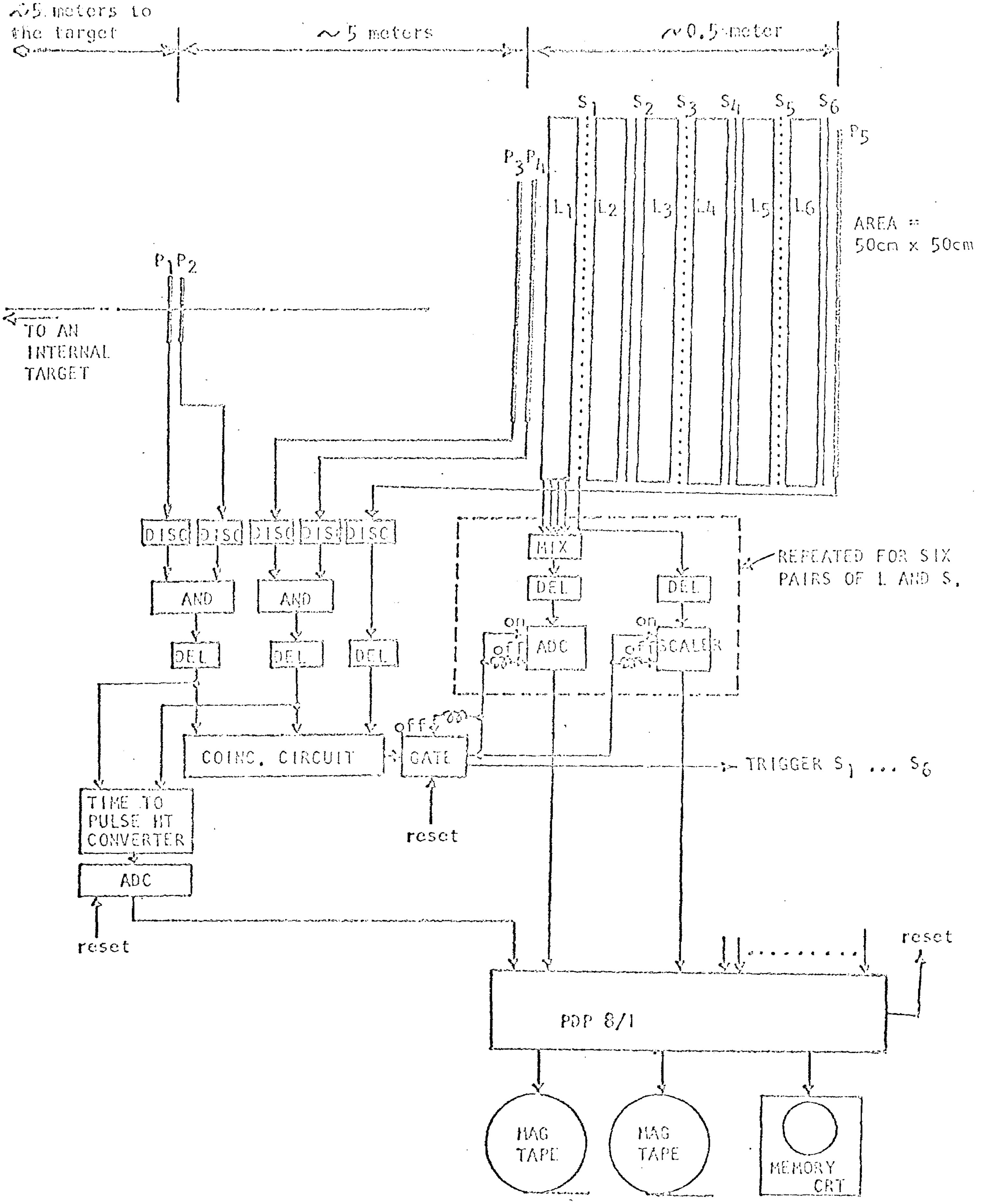

~5 meters to the target
~5 meters
~0.5 meter
S_1 S_2 S_3 S_4 S_5 S_6
P_5
P_3 P_4
L_1 L_2 L_3 L_4 L_5 L_6
AREA = 50cm x 50cm
P_1 P_2
TO AN INTERNAL TARGET
DISC
AND
DEL
MIX
REPEATED FOR SIX PAIRS OF L AND S.
on
off
ADC
SCALER
COINC. CIRCUIT
GATE
TRIGGER S_1 ... S_6
reset
TIME TO PULSE HT CONVERTER
PDP 8/I
MAG TAPE
MEMORY CRT

Figure 3

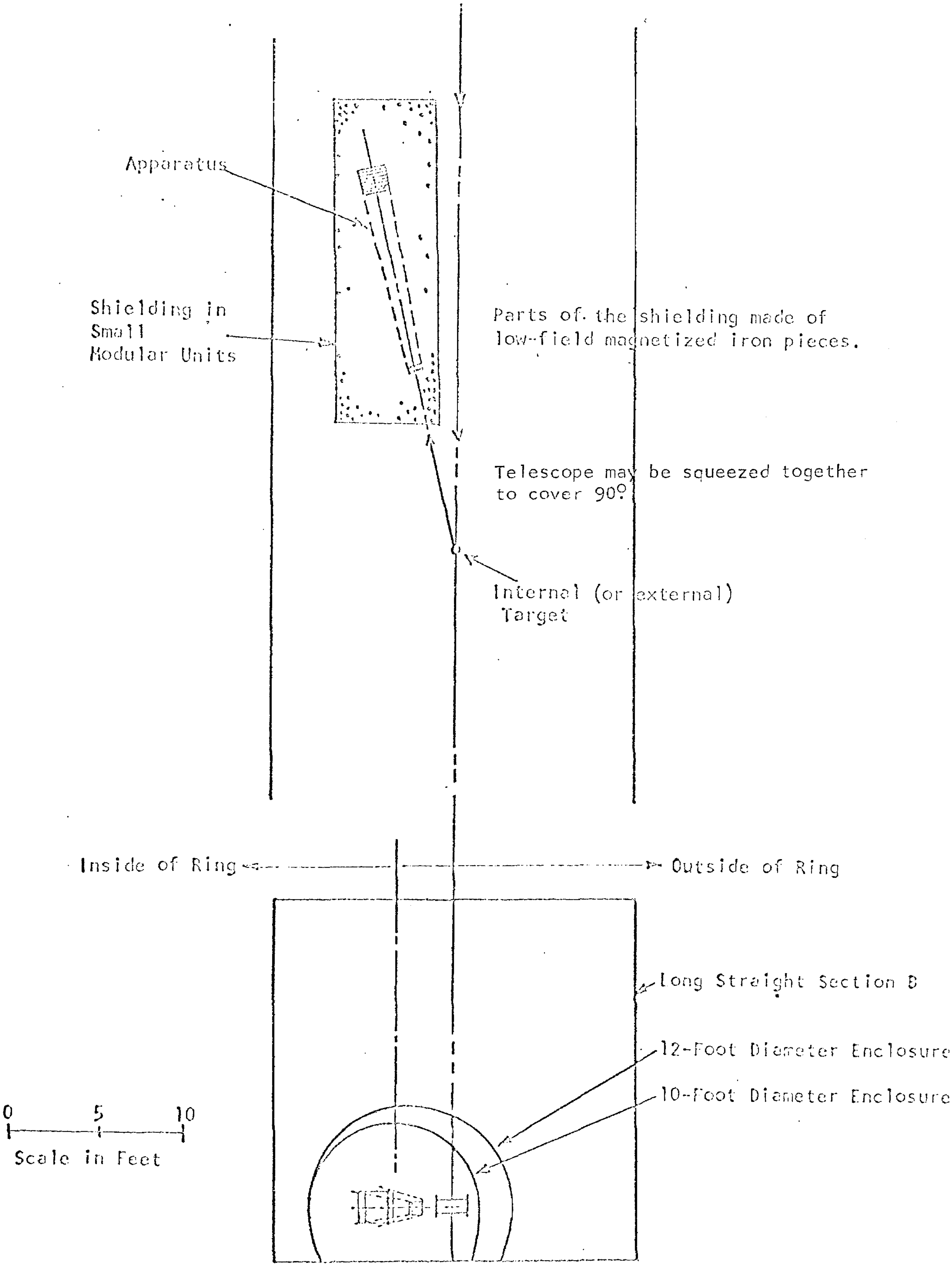

Apparatus
Shielding in
Small
Modular Units
Parts of the shielding made of
low-field magnetized iron pieces.
Telescope may be squeezed together
to cover 90°
Internal (or external)
Target
Inside of Ring
Outside of Ring
Long Straight Section B
12-Foot Diameter Enclosure
10-Foot Diameter Enclosure
0
5
10
Scale in Feet

Figure 4

A QUARK WAY TO ASYMPTOPIA*

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and

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Abstract: A phenomenological quark model of the behavior of the hadron-hadron interaction cross sections at intermediate and "asymptotic" energies is proposed. The model gives nearly constant cross sections at intermediate energies and increasing cross sections at asymptotic energies. Some implications of the model and their experimental tests are discussed.

*Work supported in part by the U.S. Atomic Energy Commission.

The surprising results on the behavior of the meson-nucleon total cross sections at the Serpukhov energies[1] and certain inconsistencies in the cosmic-ray data at energies above 100 GeV[2] seem to forebode the coming of still more surprises with the construction of new proton machines with another order of magnitude increase in the available energy.

In this note we briefly discuss a phenomenological model of the behavior of the hadron-hadron interaction cross sections at "high" energies. We divide the behavior into three phases. First, the low energy phase (phase-I) where the cross sections are mainly controlled by the presence of resonance channels[3]; or, in terms of the quark model, the interactions occur via bound states of the quarks. In this phase the cross sections decrease with energy[3]. In the second phase (phase-II), the quark bindings begin to dissolve as the interaction energy increases and the hadrons become more and more "ionized"[4]. Naively speaking, the ionization energy would be equal in the CM system to the sum of masses of the quarks excited into real and/or virtual continium states and the ionization process most likely occurs over a wide range of the interaction energy. And in the third phase (phase-III), we have asymptopia where hadrons are completely ionized and hadron-hadron interactions are via free or quasi-free quarks. Here we adopt the Cheng-Wu model[5] which predicts that the total cross sections increase with energy. We assume that free or quasi-free quarks act like Lorentz-contracted pancakes whose radius and interaction strengths both increase with energy[5].

The hadron interaction cross sections in the energy region below 30 GeV are known to fall roughly as $1/\sqrt{s}$ where s is the square of the effective mass of the interaction. However, the recent results of the Serpukhov experiments[1] show that π^-, K^- and possibly $\bar{p}$ cross sections on nuceons behave roughly as constants in the energy region above 30 GeV. The possibility of increasing cross sections at high energies has been discussed by several cosmic ray workers[6]. For example, the flux of the nucleons having no shower accompaniment at mountain altitudes has been observed to be much less than what is expected from the attenuation of nucleons in air and this "anomalous" flux of the leakage nucleons can be explained in terms of an increased cross section[6]. This is in contradiction with the expectations of the conventional description of the high energy behavior of hadron interactions[7,8].

We make the conjecture with Horn[4] that the physical mechanism responsible for the resonances is also responsible for the decrease in the total cross sections and the fact that the decrease in the cross sections stops or becomes more gradual is a reflection of the "ionization" of hadrons. For example, one may interpret the observed flattening of the $\pi^- p$ total cross section at $\sqrt{s} \approx 7.5$ GeV as being due to the excitation of one quark ($M_q \approx 6$ GeV) into a quasi-free or free state. In the present scheme, the behavior of the cross sections at phase-II energies is given by the composite of the decreasing contributions from the residual resonance channels and the increasing contributions from the free or/and quasi-free quarks. Thus, the cross sections in this phase would stay relatively constant as indeed observed in the Serpukhov experiments[1].

Recently, Cheng and Wu[5] have made the prediction that at "asymptotic" energies (i.e., our phase-III region), the hadron-hadron total cross sections will be given by $2\pi R^2$ where the effective radius (i.e., the range of the interactions) of hadrons R increases with energy $\sqrt{s}$. These authors predict $R = R_o$ Log H where R_o is a constant independent of energy and $H \sim s/(\text{Log}s)^2$. Furthermore, Cheng and Wu assert that at extremely high energies hadrons act like Lorentz-contracted pancakes which have two general regions: (1) a black core whose radius R increases with energy as given above and which becomes more absorptive with energy and (2) a partially absorptive "fringe" which extends further out than R. We assume specifically that at very high energies ($\sqrt{s} \gg$ "total" ionization energy) hadrons are completely ionized into a system of quasi-free or free quarks and that the effective size of these quarks is given by the Cheng-Wu formula: we assume that the hadron-hadron interaction cross sections at these energies are given by the additivity hypothesis[9] whereby the forward scattering amplitude for the hadron-hadron interactions is given by the sum of all possible two-body quark-quark scattering amplitudes.

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We note that the Cheng-Wu effects[5] may be "amplified" by several times in hadron-nucleus interactions. This amplification would come out because of the sizable increase in s in nucleus interactions. The exact mechanisms by which the nucleus provides the additional energy are not known[10] but we take the view that the energy increase in one form or another reflects the recoil (partial or total) of the nucleus. We consider two plausible means by which the nucleus transfers energy to the interaction: (1) the so-called linear cascade which increases the effective mass of the incoming particle and (2) the Cheng-Wu growth of particle size which increases the effective mass of the target particle.

On the basis of certain similarities between the nucleon-induced events in nuclei of widely varying A, Kaplon and Ritson[11] have made the observation that most of the particles produced in high energy nuclear interactions are well collimated and they interact simultaneously in the subsequent collisions. In the extreme case ("Kaplon-Ritson" limit) where the entire energy $\sqrt{s_o}$ of the initial collision is incident simultaneously on a target, the CM energy $\sqrt{s_1}$ of the new collision would be increased according $s_1 = s_o + 2E_oM_t + M_t^2$ or $s_n = s_o + 2E_o(nM_t) + (nM_t)^2$ for the n-th successive collision. It is seen that the CM energy is nearly doubled for n=3 if the incident energy E_o is 200 GeV assuming a stationary nucleon target. A more realistic form of the linear cascade may be interactions in which the incoming particle imparts a small longitudinal momentum recoil $\Delta_{||}$ to the target[12]. In such peripheral collisions, the major part of the collision energy may stay concentrated both in time and in space as the linear cascade progresses through the nuclear matter. In these collisions, the CM energy would increase according $s_1 \approx s_o + 2E_o\Delta_{||}$ or in the n-th successive collision $s_n \approx s_o + 2E_o(n\Delta_{||})$ where the recoil momentum is assumed to be less than the target mass.

In contrast to the linear cascade in which the effective mass of the incident "particle" grows through multiple interactions, the Cheng-Wu growth of the size of the interacting particles would mean an effective increase in the target mass. Because of the Lorentz-contraction and the Cheng-Wu growth of the particle size, the target nucleus would look like a large black disc to the incoming particle and a sizable fraction of the nuclear mass may participate in the reaction as a single unit.

Since the two mechanisms described above would "bootstrap" each other, a sizable fraction of hadron-nucleus interactions in the 200-500 GeV energy range may involve the entire nuclear mass as the target and we assert that in these reactions the incoming particle ionizes and creates a local "sea" of free or quasi-free quarks. It is probable then that many of these quarks are emitted in the laboratory system more or less isotropically with a relatively low energy. We note that in the 200-500 GeV reaction $p + Cu \rightarrow 3q + Cu$, quarks can be emitted with a 20 GeV/c momentum at $\theta_L = 180^\circ$ or with a momentum of 40-50 GeV/c at $\theta_L = 90^\circ$. The laboratory momentum distribution of quarks on the basis of the phase space available in the reaction is shown in Fig. 2. One may visualize the situation in which the momentum distribution (curves I and II in the figure) is made of a gaussian-like (isotropic in angle) distribution peaked at 20-30 GeV/c and a skewed distribution similar to the proton target distribution (curve IV in the figure). Dynamically, this situation would correspond to emission of "spectator" quarks with Fermi momenta and to scattering of the interaction quarks which presumably participate more actively in the interaction than the spectators.

Grigorov *et al.*[6] have measured the proton-C^{12} total inelastic cross section in their Proton series experiments. The actual quantity measured was the ratio of the flux of singly arriving protons with a given integral energy with and without a 30.6 g/cm^2 graphite absorber in a calorimeter. The attenuation of protons obtained in this way would correspond to a difference between the total cross section and the elastic or quasi-elastic cross section. The observed value shows an increase of about 20% in going from 20 GeV to 500 GeV. This value is an order of magnitude less than the increase one would expect from the present model if pure phase-III is assumed. However, we believe that because of certain technical problems, the Russian data indicate only a portion of the actual increase in the cross section[13] and it suffices to make the observation that the Russian results indicate a sharp rise in the cross section above 100 GeV.

Several high energy cosmic-ray pictures in a bubble chamber[14] and in emulsions[15] seem to show possible examples of phase-III interactions in which particles with a momentum as large as 10 GeV/c are emitted at large angles in the laboratory system. Other possible evidences for phase-III interactions have been discussed by Kaufman and Mongan[16] and Smorodin[2]. These authors interpret, among others, the apparent discrepancy between the satellite-observed and the EAS-based data on the energy spectrum of the primary cosmic-ray nucleons as being due to production of "passive" or "less-ionizing" particles at energies above a few hundred GeV.

Finally, we note that a simple experimental test of the present model (phase-III interactions) would consist of looking for fast ($p > 2$-3 GeV/c) particles (preferably, "less-ionizing" particles) at large laboratory angles in high-energy hadron-nucleus interactions. At large angles ($\theta_L \gtrsim 90^o$), one has the important advantages of being able to use low-energy particle detection techniques and of coping with much lower energy backgrounds.

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References

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4. D. Horn, Physics Letters 31B(1970)30.
5. Hung Cheng and Tai Tsun Wu, Phys. Rev. Letters 24(1970)1456.
6. N.L. Grigorov, Bull. Acad. Sci. USSR Phys. Ser. 29(1965)1483; N.L. Grigirov and V.Ya. Shestoperov, Bull. Acad. Sci. USSR Phys. Ser. 28 (1964)1668; N.L. Grigorov *et al.*, Kosmicheskie Issledovaniya 5(1967) 383,395,420.
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8. S.D. Drell, preprint SLAC-PUB-745 (1970).
9. H.J. Lipkin and F. Schek, Phys. Rev. Letters 16(1966)71.
10. D.E. Dorfan *et al.*, Phys. Rev. Letters 14(1965)995.
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Figure Captions

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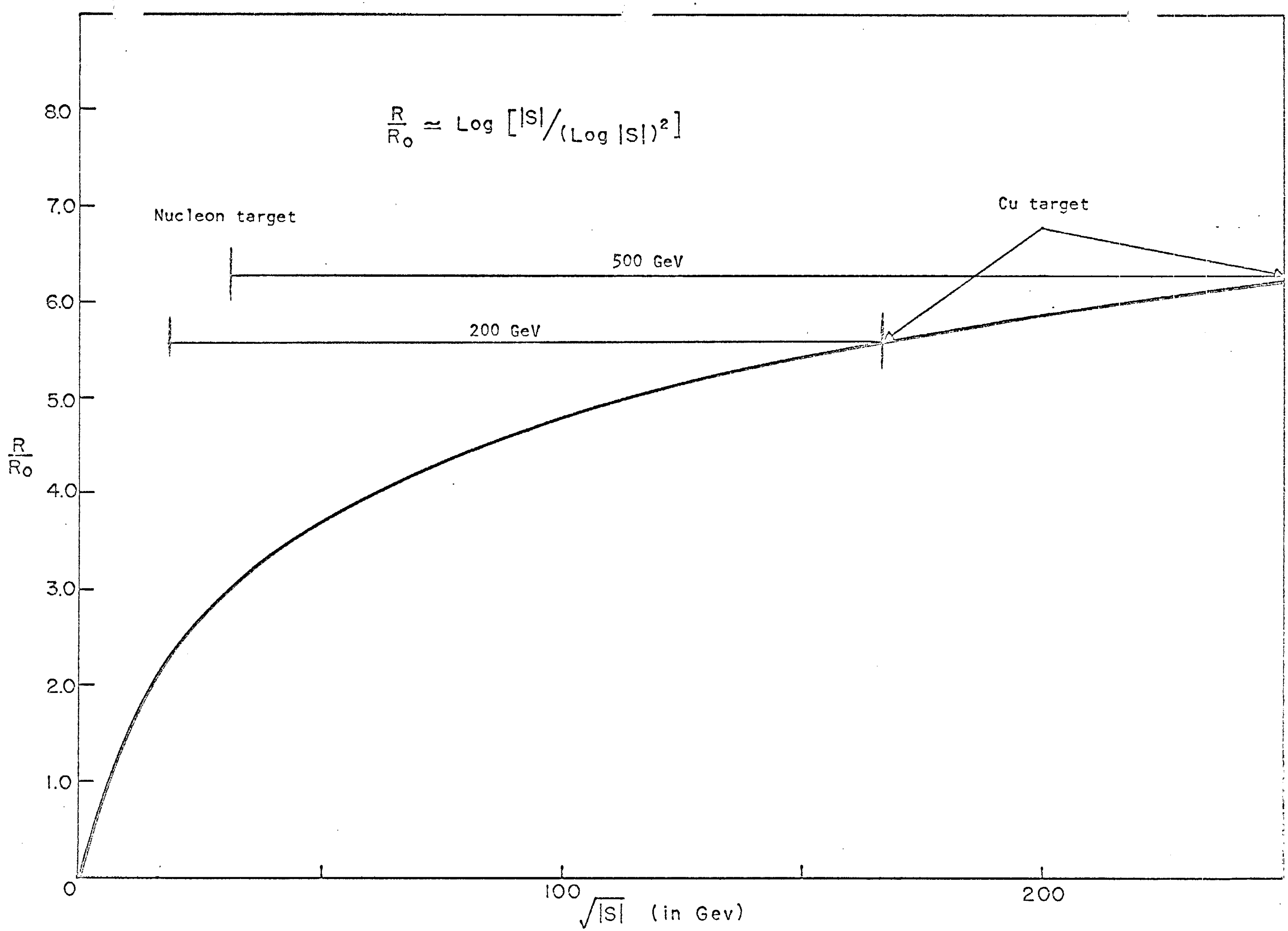
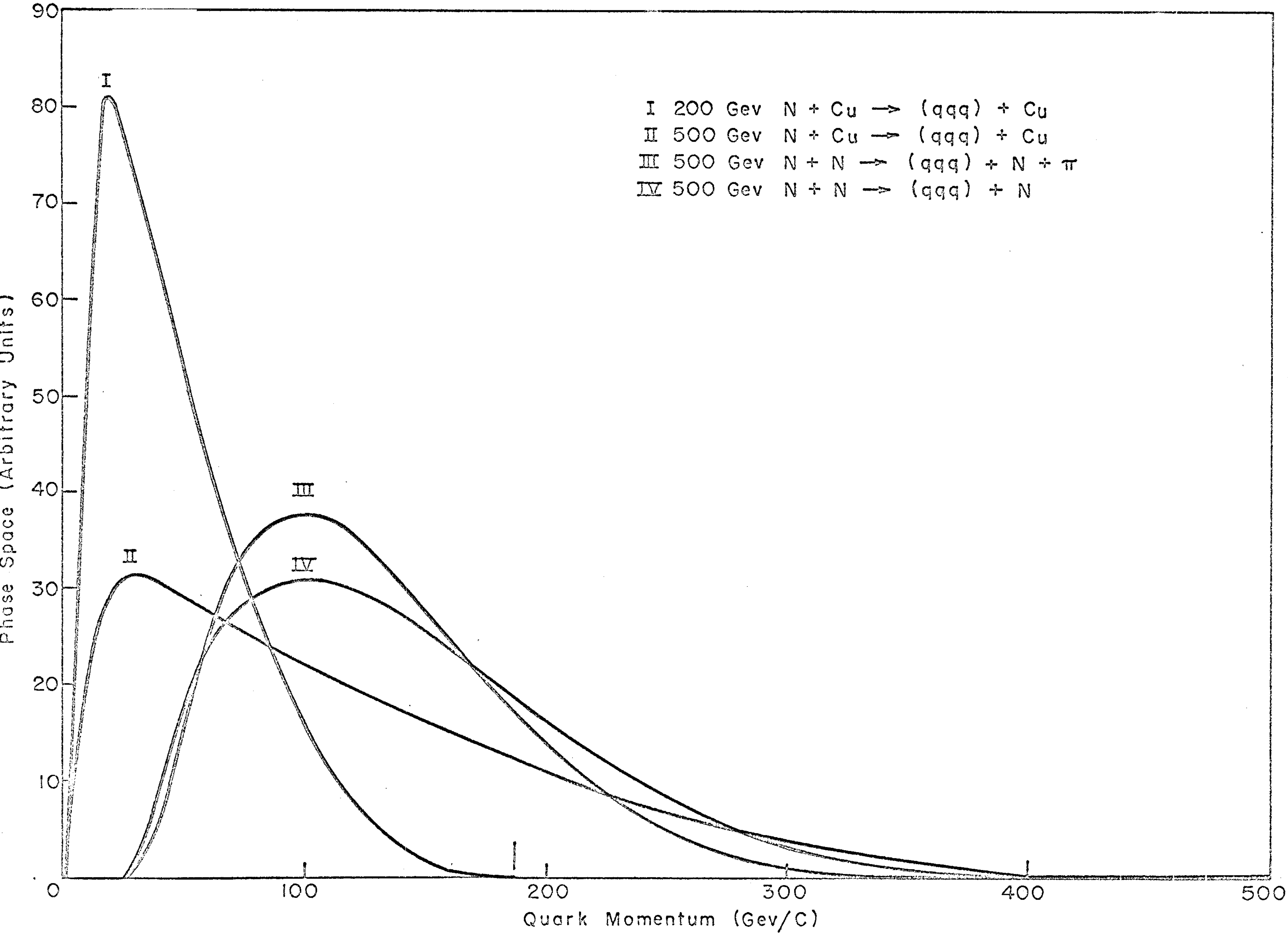


$\frac{R}{R_o} \simeq \text{Log}\left[|S|/(\text{Log}\,|S|)^2\right]$
Nucleon target
Cu target
500 GeV
200 GeV
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
$\frac{R}{R_o}$
$\sqrt{|S|}$ (in Gev)


I 200 Gev N + Cu → (qqq) + Cu
II 500 Gev N + Cu → (qqq) + Cu
III 500 Gev N + N → (qqq) + N + π
IV 500 Gev N + N → (qqq) + N
I
II
III
IV
Phase Space (Arbitrary Units)
Quark Momentum (Gev/C)
0
10
20
30
40
50
60
70
80
90
100
200
300
400
500

A QUARK WAY TO ASYMPTOPIA*

YOUNG S KIM

Physics Department, Ohio State University, Columbus, Ohio

and

NOWHAN KWAK

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Abstract: A phenomenological quark model of the behavior of the hadron-hadron interaction cross sections at intermediate and "asymptotic" energies is proposed. The model gives nearly constant cross sections at intermediate energies and increasing cross sections at asymptotic energies. Some implications of the model and their experimental tests are discussed.

*Work supported in part by the U.S. Atomic Energy Commission.

The surprising results on the behavior of the meson-nucleon total cross sections at the Serpukhov energies[1] and certain inconsistencies in the cosmic-ray data at energies above 100 GeV[2] seem to forebode the coming of still more surprises with the construction of new proton machines with another order of magnitude increase in the available energy.

In this note we briefly discuss a phenomenological model of the behavior of the hadron-hadron interaction cross sections at "high" energies. We divide the behavior into three phases. First, the low energy phase (phase-I) where the cross sections are mainly controlled by the presence of resonance channels[3]; or, in terms of the quark model, the interactions occur via bound states of the quarks. In this phase the cross sections decrease with energy[3]. In the second phase (phase-II), the quark bindings begin to dissolve as the interaction energy increases and the hadrons become more and more "ionized"[4]. Naively speaking, the ionization energy would be equal in the CM system to the sum of masses of the quarks excited into real and/or virtual continium states and the ionization process most likely occurs over a wide range of the interaction energy. And in the third phase (phase-III), we have asymptopia where hadrons are completely ionized and hadron-hadron interactions are via free or quasi-free quarks. Here we adopt the Cheng-Wu model[5] which predicts that the total cross sections increase with energy. We assume that free or quasi-free quarks act like Lorentz-contracted pancakes whose radius and interaction strengths both increase with energy[5].

The hadron interaction cross sections in the energy region below 30 GeV are known to fall roughly as $1/\sqrt{s}$ where s is the square of the effective mass of the interaction. However, the recent results of the Serpukhov experiments[1] show that π^-, K^- and possibly $\bar{p}$ cross sections on nuceons behave roughly as constants in the energy region above 30 GeV. The possibility of increasing cross sections at high energies has been discussed by several cosmic ray workers[6]. For example, the flux of the nucleons having no shower accompaniment at mountain altitudes has been observed to be much less than what is expected from the attenuation of nucleons in air and this "anomalous" flux of the leakage nucleons can be explained in terms of an increased cross section[6]. This is in contradiction with the expectations of the conventional description of the high energy behavior of hadron interactions[7,8].

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References

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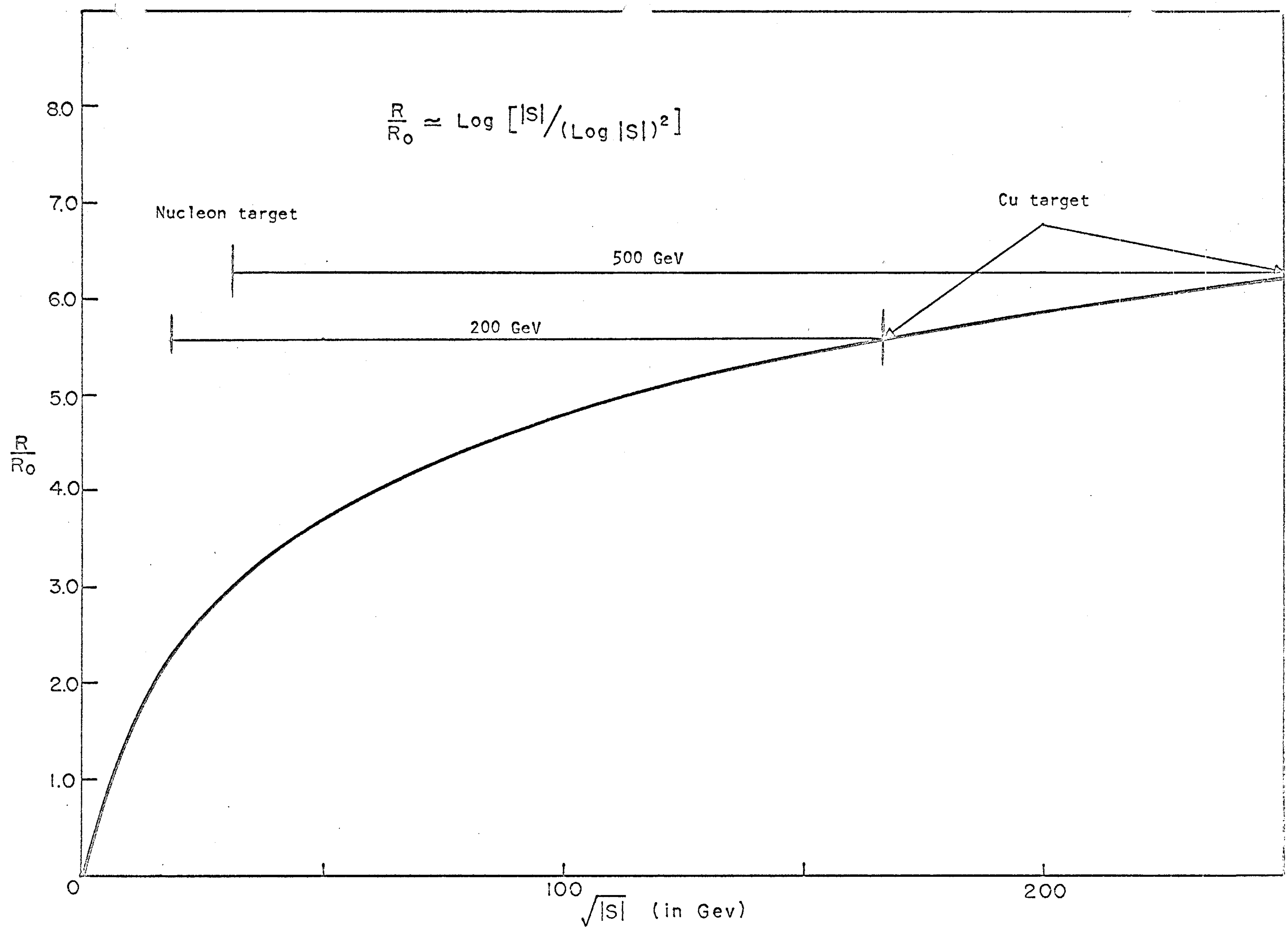
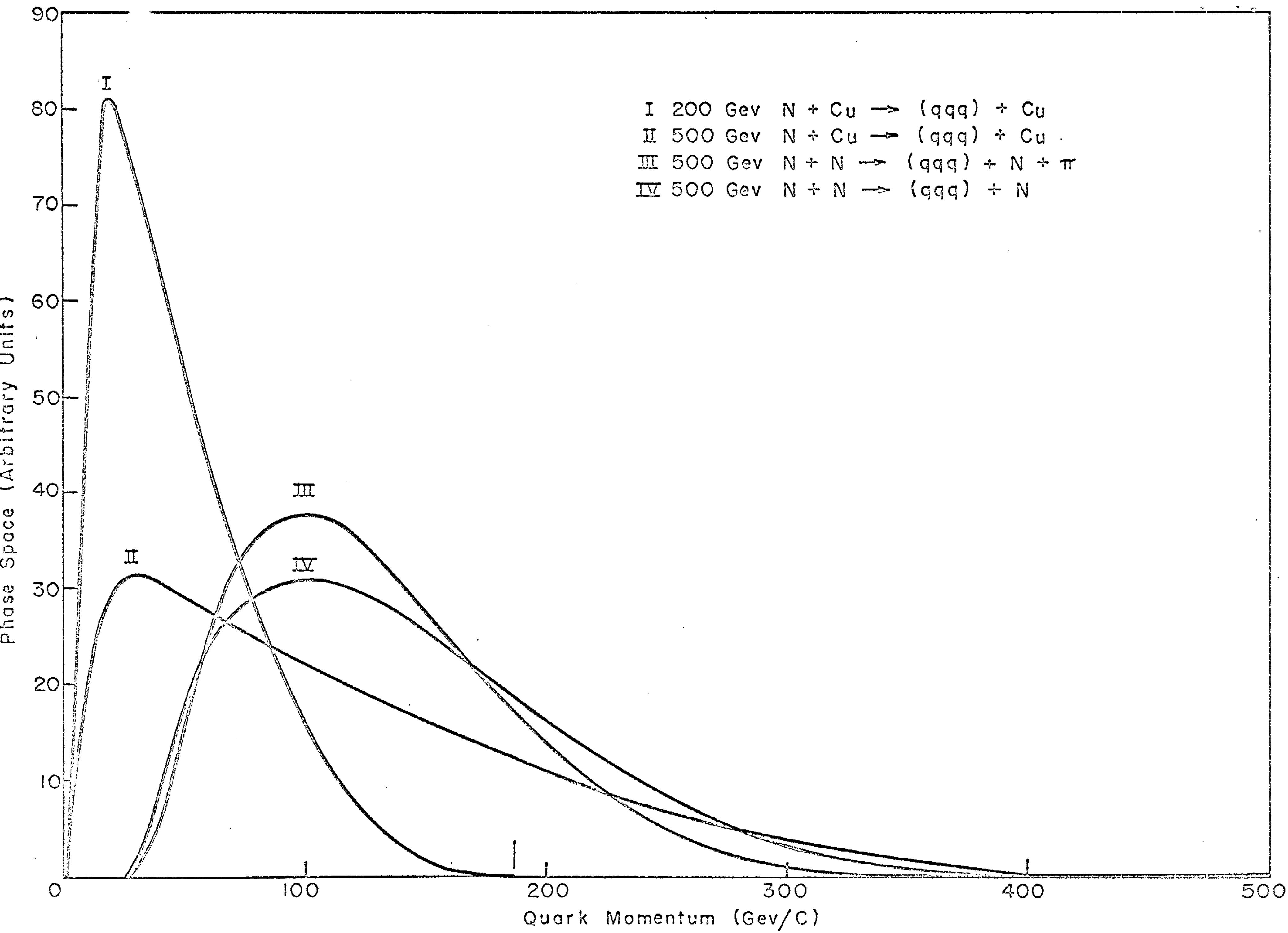

$\frac{R}{R_o} \simeq \mathrm{Log}\left[|S|/(\mathrm{Log}\,|S|)^2\right]$
Nucleon target
Cu target
500 GeV
200 GeV
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
$\frac{R}{R_o}$
$\sqrt{|S|}$ (in Gev)



I 200 Gev N + Cu → (qqq) + Cu
II 500 Gev N + Cu → (qqq) + Cu
III 500 Gev N + N → (qqq) + N + π
IV 500 Gev N + N → (qqq) + N
I
II
III
IV
Phase Space (Arbitrary Units)
Quark Momentum (Gev/C)
0
10
20
30
40
50
60
70
80
90
100
200
300
400
500